

Clinical Studies

Gender influences on spine loads during complex lifting

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Abstract

Background context: Previous research has documented differences in spine loading between genders when the imposed load is normalized relative to the size of the person. However, under realistic work conditions the magnitude of the load handled is seldom adjusted relative to worker anthropometry. Thus, there is a void in our knowledge in that we do not understand how material handling influences spine loading and potential risk of injury as a function of gender under realistic lifting situations.

Purpose: To evaluate the differences in spine loading between men and women when exposed to similar workplace demands.

Study design: A laboratory study was conducted to investigate the biomechanical responses during realistic free-dynamic lifting tasks when subjects lifted from origins and destinations that were either fixed or set relative to the subject's anthropometry.

Patient sample: Twenty men and 20 women asymptomatic for low back pain were recruited to participate in the study.

Outcome measures: The three-dimensional spine loads were predicted from a well-established electromyography-assisted model.

Methods: Both genders completed a series of symmetric and asymmetric (60-degree clockwise) lifts that originated from two shelf heights ("relative" to knee height and "set" at 35 cm from floor) and terminated at one of two destination heights ("relative" to waist and "set" 102 cm from the floor). Three levels of box weight were investigated (6.8, 13.6 and 22.7 kg).

Results: Men had significantly greater compression forces than women (about 640 N). Loading differences between genders were further magnified by several of the workplace factors. The differences between men and women were even greater when lifting either of the heavier loads from the lower fixed shelf (more than 50% greater).

Conclusions: It is apparent that men produce the greater loads on their spines during lifting. However, engineering controls, such as adjustable workplace layout or less weight lifted, may reduce or eliminate gender-specific differences in spine loads. Furthermore, the differences in spine loads appear to be a result of kinematic trade-offs and muscle coactivity differences in combination with unequal body masses between genders. However, when the loads were put into context of the expected tolerances of the spine, women were found to be at increased risk of injury, especially when lifting heavy loads or under asymmetric lifting conditions. Collectively, the results indicate the need to account for differences between the genders when designing the workplace. © 2003 Elsevier Science Inc. All rights reserved.

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Introduction

Over the past several decades, women have increasingly undertaken physically demanding jobs that have traditionally been performed primarily by men [1]. Although job requirements do not discriminate between genders, there is

reason to expect that the biomechanical effect on the worker may differ as a function of gender. For example, female lifting strength ranges between 40% and 73% of male strength [2–9]. Women also have lower lateral bending and axial twisting strength [2,7,10–12]. Such factors as anthropometry may contribute to strength differences between genders, and it is important that ergonomists, biomechanists and occupational medical personnel also consider inherent gender biomechanical differences when workers perform material handling tasks.

Differences in strength and anthropometry between men and women may influence the trunk motions, muscle activities and subsequent spine loads. For example, more extreme postures (forward flexed or asymmetric) result in greater external trunk moments as well as alter the muscle mechanics of the extensor muscles [13,14]. Furthermore, recruitment of nonprimary extensor muscles, such as the internal oblique and latissimus dorsi muscles, will complicate the loading pattern, because these muscles contribute significantly to shear as well as contribute a mechanical advantage to offset the external lifting moment. This also results in increased antagonistic contraction [15]. Thus, the combination of muscle coactivity patterns and trunk kinematics produce spinal loads during lifting that may be dependent on an interaction between the genders and the workplace factors.

To date, few studies have investigated whether differences in spine loading exist between men and women when performing a common lifting task. Until recently, only four studies [13,16–18] have considered the influence of gender on the resulting spine loads. In two of the studies [13,18], a simple two-dimensional static model was used to estimate the loads and consider body mass differences but not differences in muscle actions. Two other studies [16,17] evaluated the extensor moments generated during lifting. Recently, Marras et al. [19] found that relative loading differences between the genders depended on the degree of musculoskeletal control required during the exertion. When sagittally symmetric lifting motions were restricted to the torso (eg, subject were not able to move their hips), spine loading differences were directly attributable to body mass differences. However, when more kinematic freedom was allowed, the relationship between external moment (or body mass) and spine loading became much more complicated, with female spine loading increasing compared with that of men. This study will extend these investigations to three-dimensional loading conditions as would be expected in industrial tasks.

Hence, the objectives of the current study are three-fold: 1) to assess the magnitude of the differences in spine loads that exist for women and men; 2) to determine how the impact of gender might be altered by workplace adjustments and 3) to determine if any differences exist that may be attributed to biomechanical compensations or adjustments (eg, trunk kinematics and muscle co-activity).

Methods

Approach

Subjects performed a series of sagittally symmetric and asymmetric lifts from set and relative (to body size) origins to set and relative destinations while their feet remained stationary on a forceplate. In this manner it was possible to assess the impact of workspace adjustment on spine load as a function of gender.

Participants

Twenty men and 20 women, asymptomatic for low back pain, participated in the study. The mean (SD) age, weight and height for the men were 23.5 (3.7) years, 177.0 (9.1) cm and 74.0 (14.0) kg, and for the women were 24.3 (7.2) years, 166.5 (5.6) cm and 62.4 (8.2) kg, respectively.

Experimental design

The independent variables were box weight, lift origin height, lift destination height and task asymmetry. Subjects lifted boxes weighing 6.8, 13.6 and 22.7 kg from a shelf (origin) at 35 cm from the floor (set lift origin) or relative to knee height (relative lift origin) up to two sagittally symmetric destination heights (102 cm from the floor or relative to waist height). The origin shelf was positioned at two task asymmetries: sagittally symmetric and 60-degree clockwise (relative to the sagittal plane).

The dependent variables consisted of the estimated three-dimensional spine loads (compression, lateral shear and anterior-posterior [AP] shear) that were computed using an electromyography (EMG)-assisted biomechanical model developed in the Biodynamics Laboratory over the past 18 years [20–28]. The EMG-assisted model has been recently customized so that it more accurately represents gender-specific anthropometry. Model incorporation of estimates for cross-sectional areas and muscle origins and insertions of the 10 trunk muscles for men and women separately provides the most realistic representation of the trunk muscle mechanics to date, as well as accounts for anatomical differences between genders [29,30]. For the current study, muscle gain predictions were around 48 N/cm² for both genders with the values of R-squared and average absolute error between the measured and predicted trunk moments being above 0.88 and 13 Nm, respectively. Thus, the performance variables indicated high model fidelity for both genders.

Apparatus

The lumbar motion monitor measured the trunk motion characteristics during the lifting tasks. The lumbar motion monitor is essentially an exoskeleton of the spine in the form of a triaxial electrogoniometer that measures the instantaneous three-dimensional position, velocity and acceleration. For more detail about the design, accuracy and application of the lumbar motion monitor, refer to Marras et al. [31].

The muscle activities of the 10 trunk muscles (right and left muscle pairs of latissimus dorsi, erector spinae, rectus abdominus, external obliques and internal obliques) were collected through bipolar electrodes using standard EMG techniques [32]. Standard locations of electrode placement are presented in Marras and Mirka [33]. The EMG signals were preamplified, high-passed filtered at 30 Hz, low-passed filtered at 1,000 Hz, rectified, integrated by means of a 20-ms sliding window hardware filter, and collected (post-processed) at 100 Hz.

A forceplate was used to measure the kinetic variables during the lifts. A set of electrogoniometers were used to accurately measure the position of the L5–S1 relative to the center of the forceplate as well as the participant's pelvic/hip orientation, corresponding to hip tilt and rotation (abduction). The forces and moments are translated and rotated from the forceplate to L5–S1 by methods developed by Fathallah et al. [34]. A picture of an instrumented subject is shown in Fig. 1.

Data analyses

Descriptive statistics were computed providing means (SDs) as a function of gender and the various combinations of independent variables. Repeated-measures analysis of variance statistical analyses were performed on all the dependent variables. For all significant independent variables, post-hoc analyses (Tukey multiple pairwise comparisons) were performed to determine the source of the significant effect(s) ($\alpha < 0.05$).

Results

A summary of the statistically significant differences for the three-dimensional spine loads as a function of gender

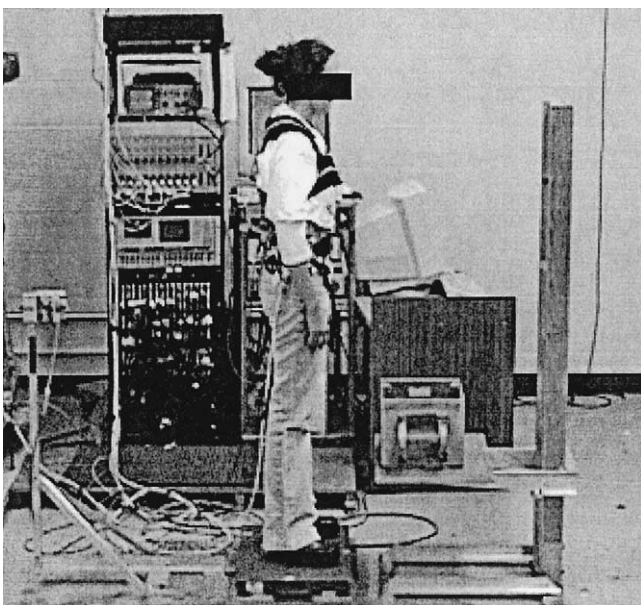


Fig. 1. Subject performing lift while instrumented with the experimental data collection apparatus.

and the experimental factors is shown in Table 1. The statistical analyses indicated that each of the experimental factors (independent of gender) significantly impacted the three-dimensional loads. As expected, increases in box weight, lower origin heights, greater task asymmetry and, to a lesser extent, higher destination heights resulted in greater three-dimensional spine loads.

On average, men's compressive loads were greater than those generated by women by 640 N (12.6%). The gender differences between the compression and AP shear loads increased as the magnitude of the load lifted increased (Fig. 2). For the heaviest weight condition, the differences in compression and AP shear were 930 N and 350 N, respectively, which was less than the differences for the lower weight conditions (about 500 N in compression and 200 N in AP shear). The differences between the genders for compression (about a 800-N difference) and AP shear (about a 400-N difference) forces were substantially greater when lifting from the set lifting origin (35 cm) as compared to lifting from the relative (knee height) origin (Fig. 3).

Discussion

Previous work evaluating how men and women respond biomechanically to similar lifting demands provided the first evidence that women are not simply proportionally scaled down versions of men [19]. In other words, the differences in spine loading are not just a function of size. In that study, subjects performed controlled sagittally symmetric lifts. When the lifting was isolated to the torso, the spine load differences were directly related to the body mass differences. However, when more kinematic freedom was permitted, the relationship between spine load and body mass became more complicated because of changes in trunk co-activity and hip kinematics. The current study required much more kinematic control than the previous study.

Overall, men had significantly greater compression forces than women. Further, it appears that load weight magnified the differences between the genders. For the 22.7-kg box

Table 1
Summary of significant analysis of variance findings.

Independent variables	Peak loading		
	Compression force	Lateral shear force	AP shear force
GDR	.03*	.50	.12
ORIG	.0001*	.0001*	.0001*
DEST	.03*	.002*	.0001*
WT	.0001*	.0001*	.0001*
ASY	.0001*	.0001*	.0001*
GDR×ORIG	.02*	.35	.001*
GDR×DEST	.10	.83	.07
GDR×WT	.01*	.92	.05*
GDR×ASY	.84	.62	.11

AP = anterior-posterior; ASY = asymmetry; DEST = destination height; GDR = gender; ORIG = original height; WT = box weight.

*Values indicate significant effect at $p < .05$.

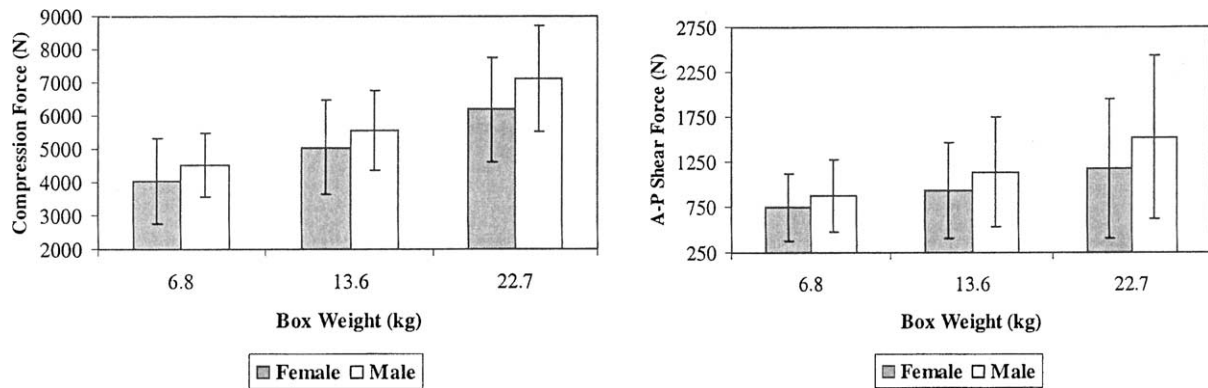


Fig. 2. Maximum compression and anterior-posterior (A-P) shear force for men and women as a function of box weight.

weight condition, the difference in compression exceeded more than 900 N, whereas the AP shear force difference was around 350 N. It should be noted that both of these dimensions of loading exceeded expected tolerances for vertebral end plate microfracture. Furthermore, when subjects lifted from a set lift origin height (eg, 35 cm from the floor), gender effects were larger than when the lift origin height was normalized to subject anthropometry (eg, knee height). In fact, under the anthropometric adjusted origin height, the spine loads were very similar for both genders, thus providing evidence regarding the value of workplace adjustability.

Because all the workplace factors also impacted the three-dimensional spine loads, it is important to understand the role of gender relative to the other factors that might influence spine loading. Fig. 4 indicates the amount of variability associated with both workplace factors and gender for the three types of spine loading in this experiment. Task asymmetry accounted for the majority of the explained variability of lateral shear, whereas gender explained only 2%. As for AP shear, the explained variability was more distributed among the variables, with gender explaining about 26% of the variability. Finally, gender explained about 15% of the variability in compression, whereas box weight approached 58%. Hence, such workplace factors as box weight

and task asymmetry had a larger impact on the spinal loads than whether the subject was male or female.

In addition to the differences in spine loading, men and women approached the lifting tasks differently with respect to trunk and hip kinematics. Women adopted a lifting style that used their hips more (about 6 degrees more of pelvic flexion [$p < .01$]), whereas much of the lifting motion for men originated from the lumbar spine (about 6 degrees more of lumbar flexion [$p < .05$]). There was also a trade-off in the motion within the pelvis and lumbar spine between men and women, as seen in Fig. 5. For the asymmetric condition, women also had more rotational motion from their pelvis than men (about 5 degrees of rotation and 9 degrees per second faster [$p < .003$]). The greater reliance on the pelvis for the women may be reflective of the limited strength capacity in lumbar region that has been previously reported in the literature [2–12].

Muscle coactivity patterns also played a role in the spine loading differences between men and women. The peak muscle activity for the extensor muscles (eg, erector spinae, latissimus dorsi and internal obliques) was significantly higher ($p < .02$) for women than men, especially for the heavier weights (eg, 22.7 kg; Fig. 6). As the weight being lifted increased, women relied on not only more erector

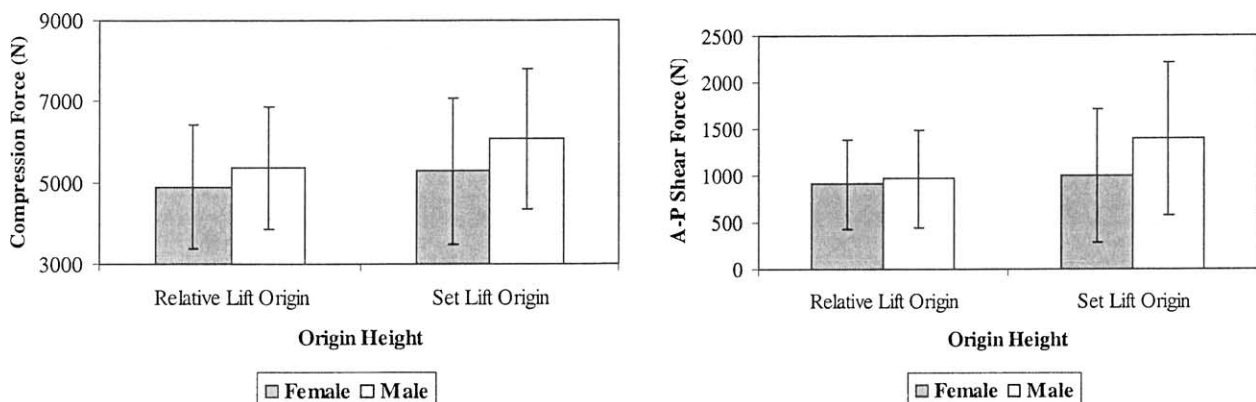


Fig. 3. Maximum compression force for males and females as a function of origin height.

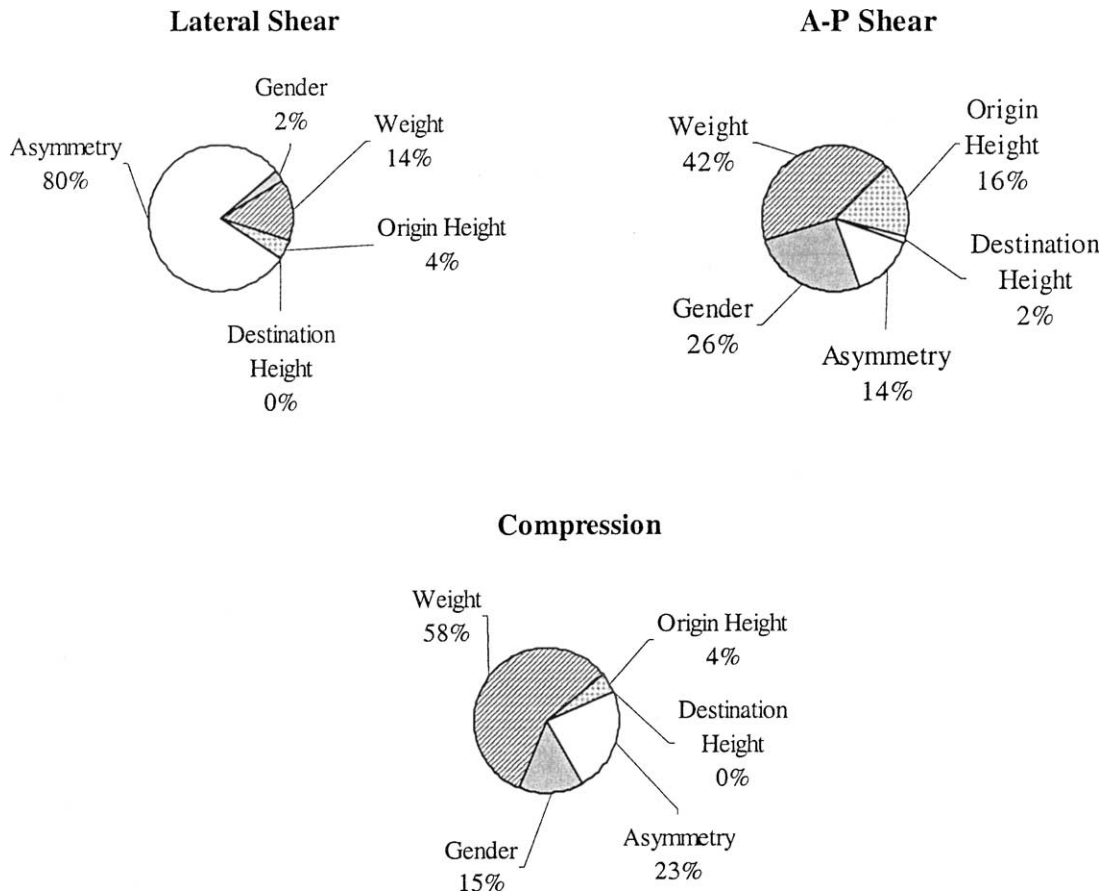


Fig. 4. The impact of gender relative to the experimental conditions for the spine loads (based on the relative amount of explained variance). A-P = anterior-posterior.

spinae activity than men, they also recruited other secondary agonist muscles to complete the lift. Both the magnitude of the loads as well as the nature (eg, shear vs. compression) of the loads were impacted by recruitment of the latissimus dorsi and internal oblique muscles because of the fact that these muscle are more obliquely oriented to the spine, resulting in more complex loading (relative to the erector spinae) [29,30,35]. Again, the increases in all the extensor

muscles, particularly at the higher weight condition, may reflect women reaching their strength capability limit. Women also had greater activity in the rectus abdominus muscles (about 7% and 5% maximum velocity contraction [MVC] for the right and left muscles, respectively) as compared to

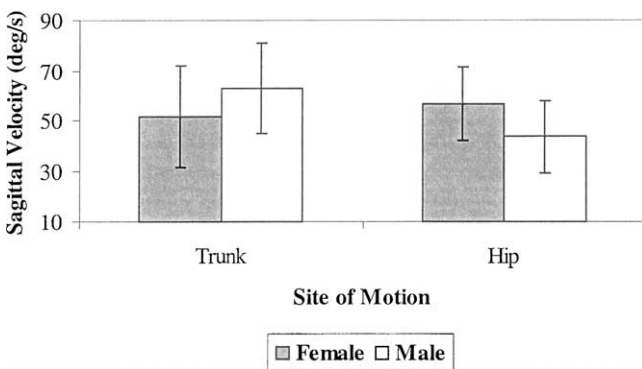


Fig. 5. Maximum sagittal trunk flexion and pelvic/hip flexion velocity for men and women.

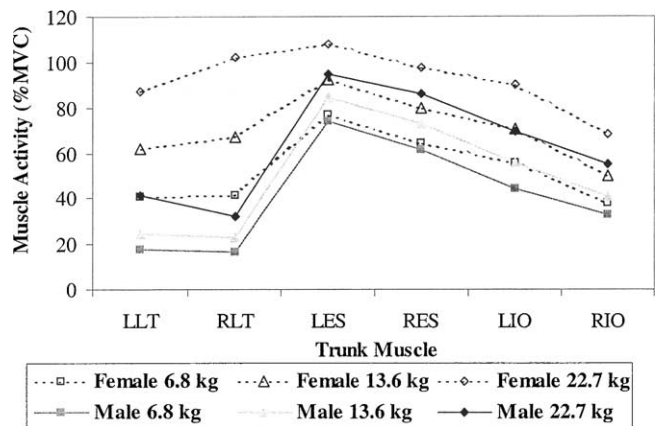


Fig. 6. Normalized muscle activity for men and women as a function of box weight. LES = left erector spinae; LIO = left internal oblique; LLT = left latissimus dorsi; MVC = maximum voluntary contraction; RES = right erector spinae; RLT = right latissimus dorsi; RIO = right internal oblique.

men. Because these muscles are antagonists, the rectus abdominus muscles contribute the spinal loads (mainly compression) but do not contribute to extensor moment generation.

We have now shown men react differently (biomechanically) to the lifting conditions than women with respect to trunk kinematics and the resulting coactivity pattern. It is the combination of trunk kinematics and muscle coactivity that results in the spinal load differences (men greater than women), that is, men flexed their trunk more but activated their muscles less. This combination resulted in higher spinal loads for men. However, the magnitude of the loads needs to be put into context, because women have lower spine tolerances (in compression) than men [36,37]. When the compression forces were compared with the tolerance values, women were at more risk of injury because they were closer to their expected tolerances. Women were 25% closer to their expected compression tolerance than men. Lifting from more asymmetric origins or higher weight influenced ($p < .04$) how close the compression forces were to the tolerance levels for the genders (an additional 7% closer to the tolerance level). Thus, based on these estimated tolerance values, women would be expected to be at a substantially higher level of risk than men when performing identical lifting tasks, which may support the field studies [38–40] that have found women were more likely to have a low back injury than men when performing similar heavy physical jobs.

Finally, it is important to consider several issues when evaluating the results of the current study. First, under actual occupational lifting conditions, the body postures of the workers may be different from those observed here because the workers' feet may not be stationary, as in this study. This foot requirement was necessary in this study in order to evaluate the model performance under the various conditions. During actual lifting tasks, workers may be able to step into the load, thus altering the external moment arm. However, many jobs have restricted access with moment arms similar to those used in this study [41]. Future studies should evaluate the differences between the genders when the feet are allowed to move.

Next, only clockwise asymmetry was evaluated. It has been found that spine loading is dependent on the direction of the asymmetry because of differences in muscle sizes and coactivity [42]. Thus, the differences between genders as a function of asymmetry may not apply to asymmetric positions to the opposite side.

Finally, the tolerance limits were predicted from an existing study that was based on cadaver values [37]. These values provide estimates rather than absolute values. Because the tolerance values were based on post-mortem specimens and were collected under static conditions, the tolerance limits represent a "best" estimate of the strength of the spine. Furthermore, the regression equations relate tolerance values to the individual's gender and age, which may neglect the impact of other factors, such as diet, genetics, physical exercise or exertion and body anthropometry. Thus, the tol-

erance values provide a rudimentary estimation of the tolerance of the spine until better estimates can be obtained.

Conclusion

The results of the current study indicate that women are not just scaled down versions of men. Rather, kinematic trade-offs and muscle coactivity differences in combination with unequal body masses resulted in the gender differences in spine loading. Women relied on more hip motion as well as required more extensor muscle activity in response to the same workplace demands as compared to the men. Most importantly, men had higher spine loads than women under more demanding conditions (eg, greater box weight or lifting from fixed height). However, a different picture appeared when evaluating the compressive loads relative to the expected tolerance levels, in that women actually were much closer to their tolerance values, especially for the heavy-weight or asymmetric lifting conditions. Study results also indicated the utility of engineering controls, because gender differences were eliminated when adjusting the lift height to anthropometric difference. Collectively, the results point out the need to account for differences between the genders when designing the workplace.

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